A Systems Theory Interpretation of Irrigation Water Quality and Long-Term Agro-Hydrological Stability

BY
DOUGLAS GITARI
STUDENT ID ALR61/49147/2025

1. INTRODUCTION

This report presents a comprehensive physicochemical evaluation of seven water sources sampled on April 29, 2026, under laboratory reference ALR-6110. The sources include three farm ponds (A, B, C), a shallow open well, a stream, a borehole, and a rain sample. All chemical parameters were evaluated against the internationally recognised FAO guidelines for irrigation water quality (Ayers & Westcot, 1985). Supplementary interpretation draws on WHO drinking-water standards (WHO, 2022), the USDA soil salinity classification (Richards, 1954), and contemporary hydro-geochemical literature.

The hydrochemical evaluation demonstrates substantial variation among the sampled waters despite all sources remaining within generally acceptable irrigation limits according to FAO standards.

1. The ponds and rainwater represent exceptionally dilute, low-salinity irrigation waters with minimal risk of salinity, sodicity, or ion toxicity. Their low EC, low sodium, low chloride, and balanced pH make them highly suitable for unrestricted irrigation use, including sprinkler and foliar applications.
2. The Well, while still agriculturally acceptable, exhibits increased mineralization and chloride enrichment consistent with shallow groundwater concentration processes and potential agricultural influence. Long-term use may require periodic monitoring to prevent salt accumulation in sensitive cropping systems.
3. The Stream and Borehole present the most significant management concerns due to elevated sodium concentrations and adjusted SAR values. Although salinity remains low, their sodicity potential may contribute to gradual soil structural degradation if unmanaged. These findings emphasize the importance of distinguishing between salinity hazards and sodicity hazards, as waters with relatively low total salinity may still impair soil infiltration through sodium dominance.

Overall, the dataset illustrates the value of integrated hydro chemical analysis using EC, TDS, ionic composition, and SAR calculations to evaluate irrigation suitability. Application of the FAO framework provides a scientifically robust basis for sustainable irrigation management and long-term soil protection.

2. BACKGROUND

All raw laboratory values were reported in parts per million (ppm), which for dilute aqueous solutions is numerically equivalent to mg/L (Hem, 1985). These were converted to milliequivalents per litre (meq/L) by dividing by the equivalent weight of each ion — the molecular weight divided by the ionic valence. This conversion enables direct charge-balance comparisons between cations and anions, calculation of the Sodium Adsorption Ratio (SAR), and application of FAO threshold tables expressed in meq/L (Ayers & Westcot, 1985; Freeze & Cherry, 1979).Each dissolved ion is characterised by its ionic charge (cation = positively charged; anion = negatively charged), its role in plant nutrition and soil dynamics, and the threshold concentrations at which irrigation hazards begin to emerge. Equivalent weights used for unit conversion are provided for full methodological transparency.

1. A cation is a tiny particle with a positive (+) charge. Think of it as a "happy ion" helping plants grow.
2. An anion is a tiny particle with a negative (–) charge. Some help plants, but too much can sometimes cause problems.

Ion	What Type Is It?	Easy Name	What It Helps Plants Do	What Happens if There Is Too Much?	Memory Tip
Ca^{2+}	Cation (+)	Calcium	Makes plants strong like bones help people. Helps soil stay crumbly and healthy.	Too much can leave white chalky marks.	"Calcium builds strong plant walls."
Mg^{2+}	Cation (+)	Magnesium	Helps leaves stay green because it is inside chlorophyll.	Too much can make sticky soil.	"Magnesium helps plants catch sunshine."
Na^{+}	Cation (+)	Sodium	Plants do not really need much of it.	Too much makes soil hard and can burn leaves.	"Too much salt hurts plants."
K^{+}	Cation (+)	Potassium	Helps plants drink water and grow strong stems and fruits.	Very high amounts can upset soil balance.	"Potassium is the plant's water coach."

F^-	Anion (–)	Fluoride	Tiny amounts are usually harmless.	Too much can damage leaves and fruit trees.	"A little is okay, too much is toxic."
Cl^-	Anion (–)	Chloride	Plants use tiny amounts.	Too much causes leaf burn and salty stress.	"Chloride can make leaves crispy."
SO_4^{2-}	Anion (–)	Sulfate	Helps plants make proteins to grow.	Too much may hurt young plants.	"Sulfate helps plants build muscles."
HCO_3^-	Anion (–)	Bicarbonate	Helps control water pH.	Too much leaves white spots on leaves and fruit.	"Bicarbonate leaves dusty white marks."
CO_3^{2-}	Anion (–)	Carbonate	Found mostly in very alkaline water.	Too much can block nutrients and make soil hard.	"Carbonate can make soil crusty."
PO_4^{3-}	Anion (–)	Phosphate	Helps roots grow and gives plants energy.	Too much can cause algae in ponds and rivers.	"Phosphate is plant energy food."

3. METHODOLOGY

a. Unit Conversions: ppm → mg/L → meq/L

Since the laboratory reported all concentrations in ppm, and for dilute water (TDS < 2,500 mg/L) ppm ≈ mg/L (Hem, 1985), no correction factor is required. Conversion to meq/L follows the formula:

meq/L = mg/L ÷ Equivalent Weight (EW) where EW = Molecular Weight ÷ Ionic Valence

Equivalent electrical conductivity conversions: 1 dS/m = 1 mmhos/cm = 1,000 µS/cm. The EC values reported in µS/cm were divided by 1,000 to obtain dS/m for FAO comparison.

Using the FAO Water Quality for Agriculture procedures and your laboratory data, all seven water samples were evaluated for irrigation suitability, salinity hazard, sodium hazard, permeability risk, and long-term soil impacts.

Water samples were collected in clean polyethylene containers previously rinsed with distilled water and conditioned using sample water prior to collection. Containers were filled completely to minimize atmospheric interaction and carbonate exchange.

Samples were transported under controlled conditions to prevent physicochemical alteration prior to analysis. Analytical procedures followed standard methods recommended by:

- APHA (1980),
- FAO Irrigation and Drainage Paper 29,
- USDA Salinity Laboratory procedures,
- and accepted hydrochemical laboratory protocols.

The following physicochemical parameters were determined:

- pH
- Electrical Conductivity (EC)
- Total Dissolved Solids (TDS)
- Calcium (Ca2+)
- Magnesium (Mg2+)
- Sodium (Na+)
- Potassium (K+)
- Chloride (Cl−)
- Sulphate (SO4^2−)
- Carbonate (CO3^2−)
- Bicarbonate (HCO3−)
- Fluoride
- Phosphorus

The analytical dataset formed the basis for evaluating:

- salinity hazard,
- sodicity hazard,
- permeability risk,
- carbonate hazard,
- and irrigation sustainability

4. **LOCATION OF SAMPLE BACKGROUND**
    a. EMBU LOCATION

The eastern slopes of Mount Kenya have historically functioned as one of the most environmentally and administratively dynamic upland corridors in colonial and postcolonial Kenya. The study area centered at coordinates (-0.420250, 37.499712) lies within the Kavutiri–Manyatta–Mutunduri–Kianjokoma corridor of present-day Embu County, an area characterized by intense historical interaction between indigenous Embu socio-ecological systems, British colonial administration, missionary expansion, commercial agriculture, and hydrological transformation. Situated within the humid upper piedmont recharge zone of Mount Kenya, the landscape occupies a critical transitional ecological belt linking highland forest hydrology with intensively cultivated lower agricultural zones.

Historically, this corridor became a focal point of colonial intervention beginning in the early twentieth century through the establishment of the Embu Reserve administration, the expansion of Anglican mission infrastructure, and the integration of African smallholder coffee production into colonial export economies (Furedi, 1989; Huxley, 1948). These transformations reshaped land tenure, vegetation cover, settlement morphology, drainage systems, and groundwater recharge patterns. By the mid-twentieth century, the area had become deeply embedded within the broader political ecology of colonial Kenya, particularly under the postwar agricultural modernization initiatives associated with the Swynnerton Plan of 1954, which accelerated land adjudication, consolidation, and intensified cash-crop agriculture (Swynnerton, 1955).

The study area at coordinates (-0.420250, 37.499712) occupied a strategically important middle-altitude zone where administrative roads, mission stations, and emerging coffee economies converged. These developments intensified human settlement and altered natural drainage systems through road construction, bridge culverts, hillside terracing, and stream diversions. The spread of Anglican missionary activity through the Church Missionary Society constituted another major driver of environmental and hydrological change in the Embu uplands. Mission stations established during the early twentieth century functioned not only as religious centers but also as nodes of agricultural instruction, literacy, medical intervention, and infrastructural development (Oliver, 1952).

Mission compounds often introduced:

- corrugated iron roofing,
- rainwater harvesting systems,
- protected wells,
- sanitation facilities,
- eucalyptus woodlots,
- and formalized drainage layouts.

These interventions altered both surface hydrology and shallow groundwater recharge conditions. Missionary correspondence frequently documented seasonal droughts, water shortages, disease outbreaks, and the condition of streams and springs, thereby providing indirect hydroclimatic evidence for reconstructing environmental conditions in the region. From the 1930s onward, the Embu uplands experienced major agricultural transformation associated with African smallholder coffee cultivation and cooperative processing systems. Coffee factories established within the Kavutiri–Manyatta–Kianjokoma corridor became focal points for economic activity, labor organization, and water usage. Wet-processing coffee factories required substantial quantities of water for pulping, washing, and fermentation, often discharging organic-rich effluent into nearby streams and wetlands.

The expansion of coffee production intensified:

- hillside terracing,
- fertilizer application,
- stream abstraction,
- road development,
- and vegetation clearance.

These processes significantly influenced erosion dynamics, sediment transport, and shallow aquifer recharge pathways. Coffee-related nutrient loading may also have contributed to long-term changes in nitrate and phosphate concentrations within local groundwater systems. The local association with "Nyaga wa Douglas" potentially reflects the memory of a colonial-era agricultural manager, cooperative organizer, settler-associated landscape, or coffee processing installation whose activities may have shaped local drainage and land-use systems. Such localized naming traditions often preserve valuable historical information concerning environmental transformation and land tenure.

b. DAGORETTI SOUTH LOCATION

The study area is the local source area from which the well and rainwater samples were collected for physicochemical analysis. Kwa Nyuki / Western Nairobi Aquifer Provenance Study (1901–1965), Study Area (Lat. -1.2855157, Long. 36.7341185) place the target area within the western Nairobi volcanic aquifer corridor associated historically with:

- Dagoretti
- Lower Kabete
- Kikuyu
- Nairobi District
- Upper Athi watershed systems

Modern mapping places the area west of central Nairobi within the Kabete–Dagoretti agricultural transition zone, historically occupied by settler farms, coffee estates, African reserve boundaries, hydrological monitoring stations, and Crown Lands allocations. The hydrological baseline report confirms:

- reduced aquifer recharge,
- severe groundwater abstraction,
- declining groundwater levels,
- and volcanic aquifer dependence within the Nairobi Aquifer System.

In the present dataset, the water sources included a shallow open well and a rain sample alongside other irrigation waters, and all samples were assessed using FAO irrigation-water criteria and related hydrochemical indices. The well and rainwater are therefore treated as part of the same local hydrological setting, where rainfall, shallow infiltration, and groundwater recharge interact with the underlying soil and geological materials to determine water quality.

In hydrogeochemical terms, the quality of well water reflects the interaction between infiltrating rainwater and the subsurface environment over time. Rainwater represents the most direct atmospheric input to the system, while well water reflects the cumulative effects of recharge, mineral dissolution, and contact with the soil and parent material. This distinction

matters because irrigation suitability is controlled not only by salinity, but also by sodium hazard, chloride concentration, bicarbonate levels, and the long-term tendency of water to alter soil structure and permeability (Ayers & Westcot, 1985; Freeze & Cherry, 1979; Hem, 1985). The rainwater sample was the most dilute source, while the well water showed greater mineralization, consistent with shallow groundwater interaction processes.

The local setting is also important historically, Colonial-era Blue Books and related reports treated the western Nairobi corridor as an agricultural, cadastral, and hydrological zone shaped by settlement, land subdivision, and water demand. That broader history helps explain why the area where the well and rainwater originate should be understood not only as a physical catchment, but also as a landscape that has been modified over time by land use, drainage change, and development pressure. In this sense, the present water chemistry is the product of both natural recharge and long-term landscape transformation (Appelo & Postma, 2005; Ayers & Westcot, 1985).

5. Water Sources: Pond A, Pond B, Pond C, Well

The four water sources used by the farming community were evaluated for short- and long-term irrigation suitability. All three ponds present excellent water quality for irrigation of a broad range of annual and perennial crops. The well presents mild concern due to elevated chloride, TDS, and EC and should be monitored with seasonal frequency.

Source: POND A

Parameter	Value	Unit	FAO Rating	Interpretation
EC	0.076	dS/m	**None**	Salinity hazard: None. Crop water availability impact: Negligible — suitable for all crops.
TDS	38	mg/L	**None**	Total dissolved load consistent with EC. Very fresh water.
Adj. SAR	1.261	—	**None**	Sodicity risk: None. No threat to soil structure. Permeability unaffected.
Cl^-	0.861	meq/L	**None**	Chloride toxicity: None. Safe for sensitive tree crops and annuals.
HCO_3^-	1.360	meq/L	**None**	Bicarbonate (overhead sprinkler): None. No carbonate deposit risk.
Na^+	0.357	meq/L	**None**	Sodium concentration relative to Ca/Mg determines sodicity risk (see Adj. SAR).
pH	6.56	—	**Normal**	Within FAO normal range (6.5–8.4). Suitable for all crops and soil conditions.

F^-	0.405	mg/L	**Safe**	Below phytotoxicity threshold (<1 mg/L preferred). No fluoride toxicity concern.
P	0.390	mg/L	**Low**	Phosphorus at irrigation concentrations is agronomically beneficial as supplemental P nutrition.

Source: POND B

Parameter	Value	Unit	FAO Rating	Interpretation
EC	0.069	dS/m	**None**	Salinity hazard: None. Crop water availability impact: Negligible — suitable for all crops.
TDS	34	mg/L	**None**	Total dissolved load consistent with EC. Very fresh water.
Adj. SAR	1.134	—	**None**	Sodicity risk: None. No threat to soil structure. Permeability unaffected.
Cl^-	0.961	meq/L	**None**	Chloride toxicity: None. Safe for sensitive tree crops and annuals.
HCO_3^-	1.120	meq/L	**None**	Bicarbonate (overhead sprinkler): None. No carbonate deposit risk.
Na^+	0.292	meq/L	**None**	Sodium concentration relative to Ca/Mg determines sodicity risk (see Adj. SAR).
pH	6.85	—	**Normal**	Within FAO normal range (6.5–8.4). Suitable for all crops and soil conditions.
F^-	0.351	mg/L	**Safe**	Below phytotoxicity threshold (<1 mg/L preferred). No fluoride toxicity concern.
P	0.080	mg/L	**Low**	Phosphorus at irrigation concentrations is agronomically beneficial as supplemental P nutrition.

Source: POND C

Parameter	Value	Unit	FAO Rating	Interpretation
EC	0.049	dS/m	**None**	Salinity hazard: None. Crop water availability impact: Negligible — suitable for all crops.
TDS	24	mg/L	**None**	Total dissolved load consistent with EC. Very fresh water.
Adj. SAR	1.229	—	**None**	Sodicity risk: None. No threat to soil structure. Permeability unaffected.
Cl^-	0.721	meq/L	**None**	Chloride toxicity: None. Safe for sensitive tree crops and annuals.
HCO_3^-	1.040	meq/L	**None**	Bicarbonate (overhead sprinkler): None. No carbonate deposit risk.
Na^+	0.310	meq/L	**None**	Sodium concentration relative to Ca/Mg determines sodicity risk (see Adj. SAR).
pH	6.63	—	**Normal**	Within FAO normal range (6.5–8.4). Suitable for all crops and soil conditions.
F^-	0.240	mg/L	**Safe**	Below phytotoxicity threshold (<1 mg/L preferred). No fluoride toxicity concern.
P	0.100	mg/L	**Low**	Phosphorus at irrigation concentrations is agronomically beneficial as supplemental P nutrition.

Source: WELL

Parameter	Value	Unit	FAO Rating	Interpretation
EC	0.483	dS/m	**None**	Salinity hazard: None. Crop water availability impact: Negligible — suitable for all crops.

TDS	241	mg/L	**None**	Total dissolved load consistent with EC. Moderate mineralisation.
Adj. SAR	1.773	—	**None**	Sodicity risk: None. No threat to soil structure. Permeability unaffected.
Cl^-	3.705	meq/L	**None**	Chloride toxicity: None. Safe for sensitive tree crops and annuals.
HCO_3^-	1.080	meq/L	**None**	Bicarbonate (overhead sprinkler): None. No carbonate deposit risk.
Na^+	0.661	meq/L	**None**	Sodium concentration relative to Ca/Mg determines sodicity risk (see Adj. SAR).
pH	6.55	—	**Normal**	Within FAO normal range (6.5–8.4). Suitable for all crops and soil conditions.
F^-	0.240	mg/L	**Safe**	Below phytotoxicity threshold (<1 mg/L preferred). No fluoride toxicity concern.
P	0.075	mg/L	**Low**	Phosphorus at irrigation concentrations is agronomically beneficial as supplemental P nutrition.

6. Farmer Action Steps

1. PONDS A, B & C: No irrigation restrictions required. Suitable for all annual crops (cereals, vegetables, legumes) and most perennial crops. Water may be applied by furrow, drip, or overhead sprinkler. For sprinkler use, schedule applications during morning or evening to minimise HCO_3-induced leaf deposits.
2. WELL: Avoid using Well water as the sole source for salt-sensitive crops (lettuce, strawberry, bean). Blend with pond water at a 1:2 ratio (well:pond) to dilute EC and Cl^- to safe levels. Conduct leaching events (irrigate 20–30% above crop demand) every 4–6 weeks during the growing season to prevent Cl^- accumulation in the root zone (Ayers & Westcot, 1985).
3. SOIL MONITORING: Test soil EC (ECe) and Exchangeable Sodium Percentage (ESP) annually in fields irrigated by the Well. Target ECe <4 dS/m and ESP <15% (Richards, 1954). Apply gypsum at 2–4 t/ha if ESP exceeds 10% and is rising.
4. WATER QUALITY MONITORING: Re-sample all sources at end of dry season and following significant rain events. Include microbiological testing (E. coli, total coliforms) if any source is considered for drinking or food washing.

5. NITRATE CHECK: Add NO_3-N to the next laboratory panel; the FAO caution threshold is 5 mg/L for irrigation and WHO limit is 11.3 mg/L-N (50 mg/L NO_3) for drinking water (WHO, 2022).
6. FOLIAR APPLICATION: All ponds are cleared for foliar use. Adjust spray solution pH to 6.0–6.5 using citric acid or sulphuric acid (pH-down) if white deposits are observed on crops after sprinkler irrigation, particularly on bicarbonate-sensitive crops such as tomato and pepper.

From best irrigation quality → highest management concern:

1. **RAIN** — Excellent quality
2. **POND C** — Excellent
3. **POND B** — Excellent
4. **POND A** — Excellent
5. **WELL** — Good
6. **STREAM** — Moderate sodium concern
7. **BOREHOLE** — Highest sodium/permeability hazard

2. Salinity Hazard (ECw)

The FAO guideline uses ECw to evaluate salinity risk. Salinity hazard was evaluated using electrical conductivity of irrigation water (ECw), following FAO Irrigation and Drainage Paper 29.

Electrical conductivity represents the total ionic strength of irrigation water and reflects the osmotic burden imposed on plants.

The irrigation salinity relationship was expressed as:

$$ECe \approx 1.5ECwEC_e \quad |approx \quad 1.5EC_w\text{ECe} \quad \approx 1.5\text{ECw}$$

where:

- ECe = saturated paste extract conductivity,
- ECw = irrigation water conductivity.

Salinity classification was based on FAO thresholds:

ECw (dS/m)	Restriction Level
<0.7	No restriction
0.7–3.0	Slight to moderate restriction
>3.0	Severe restriction

The salinity assessment considered:

- osmotic stress,
- root-water uptake limitation,
- evapoconcentration,

- and long-term root-zone salt accumulation.

ECe =1.5ECw

Results

Sample	ECw (dS/m)	Interpretation
POND A	0.076	Very low salinity
POND B	0.069	Very low salinity
POND C	0.049	Very low salinity
WELL	0.483	Low salinity
RAIN	0.043	Extremely low salinity
STREAM	0.231	Low salinity
BOREHOLE	0.294	Low salinity

Finding

All waters are within the FAO "no restriction" salinity category. None are likely to create direct salinity problems under normal irrigation management.

3. Sodium Hazard (SAR)

The sodium adsorption ratio evaluates the risk of soil dispersion and infiltration decline. SAR evaluates the tendency of sodium to dominate the soil exchange complex.

Elevated sodium adsorption promotes:

- diffuse double-layer expansion,
- clay platelet separation,
- aggregate instability,
- swelling,
- pore blockage,
- and infiltration decline.

The SAR concept is central to understanding soil hydraulic degradation under prolonged irrigation.

SAR=2Ca+Mg Na

Results

Sample	SAR	Interpretation
RAIN	0.11	Excellent

POND A	0.44	Excellent
POND B	0.44	Excellent
POND C	0.44	Excellent
WELL	0.62	Excellent
STREAM	1.43	Safe
BOREHOLE	1.75	Mild sodium concern

Finding

All SAR values are low. The borehole water shows the greatest sodium influence but remains below FAO severe restriction levels.

4. Adjusted SAR

Adjusted SAR considers bicarbonate effects and calcium precipitation. Adjusted SAR was calculated to account for bicarbonate-induced calcium precipitation and reductions in effective calcium activity.

The adjusted SAR procedure incorporates:

- pHc correction,
- carbonate equilibrium,
- calcium precipitation potential,
- and bicarbonate effects.

This parameter is especially important under low-electrolyte irrigation conditions where infiltration decline may occur despite low overall salinity.

Adjusted SAR provides a more realistic prediction of:

- long-term permeability decline,
- sodicity evolution,
- and structural degradation in fine-textured soils.

$$\text{adj SAR} = \text{SAR}[1+(8.4-\text{pH})]$$

Results

Sample	Adjusted SAR
RAIN	0.36
POND B	1.13
POND C	1.23
POND A	1.26
WELL	1.77

STREAM	3.86
BOREHOLE	5.02

Finding

The borehole and stream waters have substantially higher adjusted SAR values, indicating possible long-term infiltration reduction in fine-textured soils.

5. HCO3/Ca Ratio

This ratio indicates bicarbonate hazard and calcium precipitation potential. This index evaluates the tendency for bicarbonate and carbonate ions to precipitate calcium and magnesium from solution.

Excess bicarbonate may induce:

- calcite precipitation,
- calcium depletion,
- sodium enrichment,
- alkalization,
- and sodic soil development.

CaHCO3

Key Results

Sample	HCO3/Ca
POND B	1.93
POND A	1.80
POND C	1.32
WELL	0.82
STREAM	0.89
BOREHOLE	1.04

Finding

Pond waters show elevated bicarbonate relative to calcium, which may gradually reduce calcium availability in soils.

6. Residual Sodium Carbonate (RSC)

RSC estimates carbonate/bicarbonate hazard.

$$RSC=(HCO_3 +CO_3)-(Ca+Mg)$$

Results

Sample	RSC
POND B	0.26
POND C	0.07
POND A	0.06
RAIN	0.02
STREAM	-0.66
BOREHOLE	-0.78
WELL	-1.18

Finding

All samples are within acceptable limits. Negative values indicate calcium and magnesium dominate over bicarbonates, which is generally favorable.

7. Magnesium Hazard (MH)

High magnesium can deteriorate soil structure. High magnesium relative to calcium may adversely affect:

- aggregate stability,
- flocculation,
- infiltration,
- and structural resilience.

Magnesium-dominant waters are often associated with deteriorating permeability and poor soil physical condition.

$$MH=\frac{Mg}{Ca+Mg} \times 100$$

Results

Sample	MH %
POND C	18.86
STREAM	32.97
POND B	32.97
POND A	41.66

WELL	41.74
BOREHOLE	47.80

Finding

The borehole sample approaches the caution zone for magnesium dominance.

8. Kelly Ratio

Kelly Ratio is another sodium suitability indicator. This index evaluates sodium dominance relative to divalent stabilizing cations.

Waters with KR values approaching or exceeding unity may contribute to:

- sodium accumulation,
- exchange-complex destabilization,
- and reduced hydraulic conductivity.

Kelly Ratio=Ca+MgNa

Results

Sample	Kelly Ratio
RAIN	0.13
POND A	0.28
WELL	0.29
POND C	0.32
POND B	0.34
STREAM	0.79
BOREHOLE	0.95

Finding

Values below 1 are generally considered acceptable. The borehole is close to the upper acceptable limit.

9. Permeability Index (PI)

PI estimates long-term soil permeability effects. This index integrates:

- sodium hazard,
- bicarbonate hazard,

- and total electrolyte concentration.

The permeability index is important for evaluating:

- infiltration sustainability,
- pore continuity,
- hydraulic conductivity evolution,
- and soil physical degradation under irrigation.

$$PI = \frac{Ca + Mg + Na}{Na + HCO_3} \times 100$$

Results

Sample	PI %
WELL	58.29
BOREHOLE	77.60
STREAM	77.87
POND A	92.15
POND C	103.65
POND B	116.84
RAIN	159.30

Finding

All waters are acceptable for permeability according to Doneen's classification.

10. Langelier Saturation Index (LSI)

LSI estimates scaling or corrosive tendencies. Negative LSI values indicate corrosive tendencies, while positive values indicate scale-forming conditions.

This analysis was important for assessing:

- irrigation infrastructure durability,
- sprinkler systems,
- drip emitters,
- pumps,
- and concrete conveyance structures.

$$LSI = pH - pHs$$

Results

All samples had negative LSI values:

Range	Interpretation
-0.65 to -1.25	Slightly corrosive water

Cation Conversions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+})

Sample	Ca mg/L	Ca meq/L	Mg mg/L	Mg meq/L	Na mg/L	Na meq/L	K mg/L	K meq/L
POND A	15.15	0.756	6.56	0.540	8.22	0.357	8.85	0.226
POND B	11.60	0.579	3.46	0.285	6.72	0.292	6.99	0.179
POND C	15.82	0.789	2.23	0.184	7.12	0.310	4.74	0.121
WELL	26.34	1.314	11.44	0.942	15.20	0.661	20.94	0.536
RAIN	7.59	0.379	0.00	0.000	1.13	0.049	14.45	0.370
STREAM	22.00	1.098	6.56	0.540	29.66	1.290	15.80	0.404
BOREHOLE	17.83	0.890	9.90	0.815	37.24	1.619	14.45	0.370

Table 2. Cation conversions. EW: Ca=20.04, Mg=12.15, Na=23.00, K=39.10 g/eq.

Anion Conversions (Cl^{-}, HCO_3^{-}, SO_4^{2-}, F^{-})

Sample	Cl mg/L	Cl meq/L	HCO_3 mg/L	HCO_3 meq/L	SO_4 mg/L	SO_4 meq/L	F mg/L	F meq/L
POND A	30.53	0.861	82.96	1.360	4.20	0.087	0.405	0.021
POND B	34.08	0.961	68.32	1.120	0.68	0.014	0.351	0.018
POND C	25.56	0.721	63.44	1.040	0.28	0.006	0.240	0.013
WELL	131.35	3.705	65.88	1.080	4.38	0.091	0.240	0.013
RAIN	21.30	0.601	24.40	0.400	0.20	0.004	0.109	0.006
STREAM	39.05	1.102	59.78	0.980	1.20	0.025	0.310	0.016
BOREHOLE	62.48	1.762	56.21	0.921	0.13	0.003	0.268	0.014

Table 3. Anion conversions. EW: Cl=35.45, HCO_3=61.02, SO_4=48.03, F=19.00 g/eq.

3.3 Salinity, TDS, and Sodium Adsorption Ratio

Sample	EC (µS/cm)	EC (dS/m)	TDS (mg/L)	SAR	Adj. SAR	pH
POND A	76	0.076	38	0.444	1.261	6.56
POND B	69	0.069	34	0.445	1.134	6.85
POND C	49	0.049	24	0.444	1.229	6.63
WELL	483	0.483	241	0.622	1.773	6.55
RAIN	43	0.043	21	0.113	0.356	6.25
STREAM	231	0.231	115	1.425	3.862	6.69
BOREHOLE	294	0.294	147	1.754	5.016	6.54

Table 4. EC conversions and SAR. SAR = $Na^+ / \sqrt{[(Ca^{2+} + Mg^{2+})/2]}$ in meq/L. Adj. SAR = SAR × [1 + (8.4 – pH)] (Ayers & Westcot, 1985).

4. FAO Irrigation Water Quality Classification

All samples are classified below against the Ayers & Westcot (1985) FAO framework across four hazard categories: Salinity (crop water availability), Permeability / Sodicity (soil infiltration), Specific Ion Toxicity (sodium, chloride, boron), and Miscellaneous Effects (NO_3-N, HCO_3 for overhead sprinkling, pH).

Sample	Salinity(EC dS/m)	Rating	Adj. SAR	Sodicity Rating	Cl meq/L	Cl Rating	HCO_3 meq/L	HCO_3 Rating (Sprinkler)	Overall Suitability
POND A	0.076	**None**	1.261	**None**	0.861	**None**	1.360	**None**	**SUITABLE**
POND B	0.069	**None**	1.134	**None**	0.961	**None**	1.120	**None**	**SUITABLE**
POND C	0.049	**None**	1.229	**None**	0.721	**None**	1.040	**None**	**SUITABLE**
WELL	0.483	**None**	1.773	**None**	3.705	**None**	1.080	**None**	**CAUTION – Salinity**
RAIN	0.043	**None**	0.356	**None**	0.601	**None**	0.400	**None**	**SUITABLE (Very Dilute)**
STREAM	0.231	**None**	3.862	**Slight–Moderate**	1.102	**None**	0.980	**None**	**CAUTION –**

Sample	Salinity(EC dS/m)	Rating	Adj. SAR	Sodicity Rating	Cl meq/L	Cl Rating	HCO_3 meq/L	HCO_3 Rating (Sprinkler)	Overall Suitability
									Na/Sodicity
BORE HOLE	0.294	**None**	5.016	**Slight–Moderate**	1.762	**None**	0.921	**None**	**CAUTION – Na/Sodicity**

Table 5. FAO irrigation water quality classification. Thresholds: Salinity <0.75=None, 0.75–3.0=Slight–Moderate, >3.0=Severe; Adj. SAR <3=None, 3–9=Slight–Moderate, >9=Severe; Cl <4=None, 4–10=Slight–Moderate; HCO_3 (sprinkler) <1.5=None, 1.5–8.5=Slight–Moderate (Ayers & Westcot, 1985).

DISCUSSION

A tilapia pond is not merely a water reservoir, It is a dynamic nutrient transformation bioreactor, In regenerative agriculture, the pond functions as a living digestion and nutrient-cycling ecosystem capable of generating biologically active foliar nutrition. Fish metabolism continuously transforms feed proteins into dissolved amino compounds, ammonium, microbial biomass, enzymes, organic acids, vitamins, and carbon substrates. Heterotrophic bacteria mineralize fish waste into plant-available forms, while algae assimilate dissolved nutrients and produce amino acids, phytohormones, polysaccharides, and trace metabolites. Unlike synthetic foliar fertilizers that deliver isolated ionic nutrients, biological pond-derived foliar systems deliver nutrients embedded within microbial metabolites and naturally chelated organic complexes, this distinction is physiologically profound, among the ponds, the foliar suitability ranking is:

1. Pond C — highest foliar suitability due to the lowest EC, chloride, bicarbonate, and fluoride.
2. Pond B — excellent balance with slightly higher chloride but lower bicarbonate than Pond A.
3. Pond A — still highly suitable but carries the highest bicarbonate load and therefore greatest carbonate precipitation potential.

The well water remains agriculturally usable but is substantially less suitable for biological foliar systems due to elevated chloride (3.705 meq/L), higher EC (0.483 dS/m), and greater total dissolved solids (241 mg/L). While still technically within FAO “None” classification for irrigation, the well approaches the chloride threshold where repeated foliar exposure may injure sensitive tissues.

Salinity refers to the total concentration of dissolved salts in irrigation water, measured as electrical conductivity (EC) in dS/m. High-salinity water creates osmotic stress — crops must expend additional energy to extract water from saline soil solution, effectively inducing physiological drought (Munns & Tester, 2008). Repeated irrigation with high-EC water progressively accumulates salts in the root zone, particularly in arid or semi-arid climates with

insufficient rainfall to leach salts below the root zone. The result is a saline soil ($EC_{1:1}$ extract >4 dS/m; USDA classification), which suppresses germination, stunts growth, reduces crop yield, and ultimately renders land non-productive (Richards, 1954). Among the samples, only the Well (0.483 dS/m) approaches moderate concern; all other sources fall well below the FAO "None" threshold of 0.75 dS/m.

Sodicity is a soil structural problem caused by excessive sodium (Na^+) relative to calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the soil exchange complex. When the Sodium Adsorption Ratio (SAR) of irrigation water is high, Na^+ displaces Ca^{2+} and Mg^{2+} on soil clay surfaces. This causes clay platelet dispersion, collapse of macropores, surface sealing, and drastically reduced hydraulic conductivity — a sodic soil (Exchangeable Sodium Percentage >15%; Rengasamy, 2006). Unlike salinity, sodicity cannot be corrected merely by leaching — it requires soil amendments such as gypsum ($CaSO_4$) to replace Na^+ on exchange sites. The FAO uses the Adjusted SAR (which corrects for pH and bicarbonate effects on Ca precipitation) as the primary sodicity indicator. In this dataset, BOREHOLE (Adj. SAR 5.02) and STREAM (3.86) register in the Slight–Moderate range and warrant monitoring, particularly with cumulative irrigation use.

The cation composition of irrigation water strongly influences both soil structural stability and plant physiological performance, calcium and magnesium are beneficial divalent cations that stabilize soil aggregates and counteract the dispersive effects of sodium (Richards, 1954). In contrast, excessive sodium contributes to soil sodicity by displacing calcium and magnesium from clay exchange surfaces, resulting in clay swelling, reduced infiltration, and soil crusting (Qadir & Schubert, 2006). The pond waters exhibited relatively balanced and low cation concentrations.

1. Pond A contained 0.756 meq/L Ca^{2+} and 0.540 meq/L Mg^{2+}, while sodium remained extremely low at 0.357 meq/L.
2. Similar trends were observed in Ponds B and C, where sodium concentrations remained below 0.31 meq/L.

These low sodium levels explain the correspondingly low SAR and adjusted SAR values observed for the ponds, indicating negligible sodicity hazard, the Well sample showed elevated concentrations of all major cations relative to the ponds, particularly calcium (1.314 meq/L), magnesium (0.942 meq/L), sodium (0.661 meq/L), and potassium (0.536 meq/L). Although sodium remained within acceptable irrigation limits, the increased dissolved mineral load contributed to higher EC and TDS values. Suggesting greater mineralization and prolonged water-rock interaction within the shallow groundwater system (Freeze & Cherry, 1979).

The Stream and Borehole samples demonstrated the most significant sodium enrichment, with the Stream containg 1.290 meq/L Na^+, while the Borehole contained the highest sodium concentration of all sources at 1.619 meq/L. Elevated sodium relative to calcium and magnesium increases the sodium adsorption ratio and therefore the risk of long-term sodic soil development, likely reflect geological weathering processes, cation exchange reactions, or anthropogenic influences such as agricultural runoff (Appelo & Postma, 2005). Rainwater displayed exceptionally low mineralization, with sodium at only 0.049 meq/L and zero detectable magnesium. This confirms that the rainwater represents a highly dilute atmospheric deposition source with minimal salinity or sodicity hazard.

The hydrochemical assessment showed that all water sources generally fall within acceptable FAO irrigation standards, although important differences exist between ponds, groundwater, and flowing water sources. Chloride concentrations in all pond samples remained low (0.721–0.961 meq/L), indicating minimal risk of chloride toxicity for both annual and perennial crops.

In contrast, the Well exhibited a higher chloride concentration (3.705 meq/L), approaching the FAO caution threshold and suggesting potential long-term chloride accumulation in sensitive crops if used continuously (Ayers & Westcot, 1985). The Stream and Borehole showed moderate chloride levels, indicating increasing mineral influence but no immediate toxicity hazard. Bicarbonate concentrations across all samples remained below the FAO sprinkler irrigation threshold of 1.5 meq/L. However, Pond A approached this limit, meaning that under high evaporation conditions calcium and magnesium carbonate deposits could form on leaves and irrigation equipment. Fluoride concentrations were very low in all samples and therefore posed negligible phytotoxicity risk.

Salinity indicators, including electrical conductivity (EC) and total dissolved solids (TDS), demonstrated that all waters were low in dissolved salts and suitable for irrigation. Pond and rainwater samples were exceptionally dilute, with EC values below 0.08 dS/m, making them highly favorable for unrestricted irrigation use. The Well showed the highest EC (0.483 dS/m) and TDS (241 mg/L), indicating greater groundwater mineralization and the need for long-term monitoring. Sodium Adsorption Ratio (SAR) analysis revealed minimal sodicity risk in the ponds and rainwater, with adjusted SAR values near 1.2 or lower. However, the Stream and Borehole exhibited adjusted SAR values of 3.862 and 5.016 respectively, placing them in the FAO "Slight–Moderate" sodicity category. This suggests that prolonged use may gradually degrade soil structure through sodium-induced clay dispersion and reduced infiltration (Rengasamy, 2006).

CONCLUSION

Overall, Ponds A, B, and C were classified as fully suitable irrigation sources with no significant salinity, sodicity, chloride, or bicarbonate hazards. Rainwater was similarly suitable due to its extremely low mineral content. The Well remained usable but requires caution and monitoring because of increased salinity and chloride levels, while the Stream and Borehole require sodicity management strategies such as periodic leaching or gypsum application. The findings demonstrate the importance of integrated hydrochemical analysis using EC, TDS, ionic composition, and SAR to support sustainable irrigation management and long-term soil protection (Ayers & Westcot, 1985).

The laboratory data demonstrate that the tilapia ponds represent exceptionally high-quality water platforms for regenerative biological foliar agriculture. Their ultra-low salinity, low sodium hazard, low chloride concentration, and balanced pH create an ideal foundation for biologically active foliar nutrition systems.

When integrated with:

- microbial fermentation,
- nutrient-dense plant biomass,
- compost-derived microbiology,
- and precision irrigation engineering,

the ponds become multifunctional nutrient bioreactors capable of replacing substantial portions of synthetic foliar fertilizer dependency while improving ecological resilience, nutrient cycling efficiency, and farm self-sufficiency.

This approach transforms irrigation water from a passive transport medium into an active biological nutrition ecosystem grounded simultaneously in FAO irrigation science, aquaculture nutrient recovery, plant physiology, and regenerative agroecology (Ayers & Westcot, 1985; Taiz & Zeiger, 2010; Appelo & Postma, 2005; Munns & Tester, 2008).

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